

Results from MiniBooNE

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Abstract

The long awaited experimental results from MiniBooNE have recently been announced. This experiment tests whether neutrino oscillations can occur at a higher mass squared difference $\sim 1 \text{ eV}^2$ compared to well established observations of solar and atmospheric neutrinos. The LSND experiment has previously claimed to have observed neutrino oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$, however the results being controversial, required an independent confirmation. The MiniBooNE results settle this controversy by observing null oscillations at the said mass squared difference. These results have strong implications on existence of sterile neutrinos, CPT violation and mass varying neutrinos. We review the present status of neutrino masses and mixing in the light of this recent result.

I. INTRODUCTION

In the Standard Model (SM) of elementary particles, there are three neutrinos, one for each flavour: electron type (ν_e), muon-type (ν_μ) and the tau-type (ν_τ). They do not have electric charge and participate only in weak interactions which are responsible for processes like nuclear β -decay etc. The original standard model, not having enough knowledge of the other main physical attribute of the neutrino, namely, their mass, has left them massless. However starting from 1998, experimental measurements of neutrino oscillations have become very robust implying neutrinos do have masses, however tiny. The neutrino oscillation formula is given in terms of the mass squared differences and the mixing angle parameters of the neutrinos. For the simplest case of two flavours, denoted by a and b , oscillation probability is given by :

$$P_{ab} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m_{ab}^2 (\text{eV}^2) L_\nu (\text{Meters})}{E_\nu (\text{MeV})} \right), \quad (1)$$

with θ representing the mixing angle between the two flavours and $\Delta m_{ab}^2 = m_b^2 - m_a^2$, the mass squared difference between them. L_ν and E_ν represent the distance and the energy traversed by the neutrino respectively. Within the standard picture of three neutrinos, which we elaborate below, there can be two independent mass squared differences responsible for the observed solar and atmospheric neutrino oscillations.

One of the important challenges in this field was whether neutrino oscillations would be observed not just in neutrinos produced in astrophysical processes, but, also in laboratory-like conditions, for example, neutrinos produced at nuclear reactors or in particle accelerators. These experiments are of two types either Short-base line (SBL) or Long Base line (LBL), depending on the length neutrino traverses from the time of production to the time of detection. One of the first claims for observation of neutrino oscillations in laboratory was done by the Liquid Scintillation Neutrino Detector (LSND) experiment conducted at the Los Alamos National Laboratory, USA. However, this result soon ran in to controversy for various technical reasons¹ as well as for predicting existence of newer exotic particles called sterile neutrinos. The oscillations observed required a much larger mass difference compared to those required in solar and atmospheric oscillations and thus could only be explained by introducing a new neutrino which does not even participate in weak interactions and hence sterile.

¹ The LSND evidence soon was termed as LSND anomaly as questions were raised regarding the accuracy about background estimates, etc. The LSND collaboration has responded to most of the criticisms with elaborate checks. The evidence still persisted.

A second experiment called KARMEN failed to settle this controversy as it could not probe the entire parameter space of the LSND experiment. The MiniBooNE was designed specifically to settle this controversial issue and prove/refute the simplest and popular explanation of the LSND result *i.e* the existence of a sterile neutrino at that mass range. This April, the MiniBooNE collaboration has announced its first results after taking data for almost five years. Using statistically robust methods in their data analysis, they have found no positive signal for neutrino oscillations at mass squared difference $\Delta m^2 \sim 1 \text{ eV}^2$. This result settles the LSND controversy which has dogged the particle physics community for over a decade. However caveats still do exist as we will explain later.

In the present article, we report on this new experimental results and comment on the implications the results would have on our understanding of sterile neutrinos. The rest of the article is organised as follows : in the next section, we summarise the existing standard picture of three neutrino oscillations. The summary is not necessarily chronological in order, but we will give the dates wherever we can. In section 3, we elaborate on the LSND experimental results and their possible theoretical explanations. We also report on KARMEN’s failure to contradict/validate the LSND experiment. In section 4, we report on the first results from MiniBooNE and their implications on particle physics scenarios. We close with some remarks on future directions.

II. THE STANDARD PICTURE OF THREE NEUTRINO OSCILLATIONS

Neutrino oscillations were first proposed by Pontecorvo[1] inspired by the observed neutral K-meson oscillations. The first experimental indications of neutrino oscillations came from pioneering experiments of Raymond Davis Jr. (Nobel Laureate, 2002) measuring the neutrino flux from the Sun. The Sun, as we know produces energy through nuclear fusion, which can be summarised by the equation [2]:

$$4 p + 2 e^- \rightarrow {}^4\text{He} + 2 \nu_e + Q, \quad (2)$$

which shows four protons and two electrons fuse to form a Helium nucleus giving out energy ($Q = 26.73$ million electron volts (MeV)) and two electron-type neutrinos (ν_e). The expected number of ν_e coming from the Sun to be observed at the earth can be computed using detailed numerical computations, following the Standard Solar Model (SSM). However observed number always fell short by about 50 % compared to the expected number giving rise to the so-called ‘Solar Neutrino

Problem². The simplest solution proposed for the Solar Neutrino Problem was neutrino oscillations of Pontecorvo which are possible if neutrinos have tiny but non-zero masses. In such a case, the ν_e produced in the Sun, gets converted in to a ν_μ or ν_τ or a more exactly a linear combination of them while traversing the distance from the Sun to the detector placed on earth. It should be noted that earlier detectors were sensitive only to ν_e *i.e* they could only detect ν_e but not ν_μ and ν_τ flavours. And hence, experiments could only validate that solar electron neutrinos do convert to ν_μ and ν_τ flavours conclusively only in late 2002. This was done by a combination of experiments at SNO (Sudbury Neutrino Observatory) in Canada, which was sensitive to all the three flavours, and at Super-Kamiokande detector located in Japan[3].

However, there was still one more issue to be settled. This issue is concerned with the question how and where exactly the electron neutrinos which are produced at the core of the Sun get converted to the other flavours while traversing the distance from the centre of the Sun to the Earth's surface. In particular, taking into consideration the interaction of the neutrino with the dense matter of the Sun, another mechanism to convert ν_e to $\nu_{\mu(\tau)}$ called the MSW (Mikheyev, Smirnov and Wolfenstien) mechanism can happen other than the afore mentioned oscillations of the neutrino in vacuum. It was thus important to identify exactly which mechanism was responsible for the conversion of the electron neutrinos from the Sun as they reach the Earth. This issue was recently settled by the experiment called KamLand which observed neutrino oscillations on the earth corresponding to the mass differences of the solar neutrinos. Finally, the data from all the experiments namely, KamLand, SNO, SuperKamiokande taken together points out to a large mixing MSW solution to the solar neutrino problem. The mass-squared difference and the mixing angle are determined to be[4]:

$$\begin{aligned}\Delta m_{\text{solar}}^2 &= 7.9_{-0.28}^{+0.27}({}_{-0.89}^{+1.1}) \times 10^{-5} \text{eV}^2 \\ \theta_{\text{solar}} &= 33.7 \pm 1.3({}_{-3.5}^{+4.3}) \text{deg},\end{aligned}\tag{3}$$

where we have shown the errors bars in the 1σ (3σ) range.

Atmospheric neutrinos have been discovered in India and in South Africa in the 1960's as background for proton decay experiments. The origin of these neutrinos was traced to the interactions of cosmic rays with the atmospheric air molecules which led to the prediction for the ratio

$$\frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \simeq 2,\tag{4}$$

² This problem persisted for over thirty years.

where N_{ν_f} stands for the total number of the neutrinos corresponding to the flavour f . The bar on the top represents an anti-particle. This ratio is roughly expected to be ‘2’ based on simple analysis of Pion and Kaon decays. Detailed numerical simulations including earth magnetic field effects also confirm this ratio to be close to ‘2’. However, experiments using huge water Cerenkov neutrino detectors like IMB and Kamiokande observed a deviation from the above prediction, which can be best expressed in terms of a double ratio given by

$$R = \frac{(N_{\nu_\mu}/N_{\nu_e})_{\text{data}}}{(N_{\nu_\mu}/N_{\nu_e})_{\text{MC}}}, \quad (5)$$

where the subscript ‘MC’ for the ratio in the denominator corresponds to expectations based on Monte Carlo numerical simulations. Both IMB and Kamiokande have found this double ratio, R to be of the order of 0.6 instead of 1 as one would have expected. Neutrino oscillations were again thought to be the culprit for this discrepancy. In 1998, the Super-Kamiokande collaboration announced strong evidence for neutrino oscillations in atmospheric neutrinos with high statistics. This was one of the first evidences of neutrino oscillations with such experimental accuracy and high statistics. These experiments observed an ‘up-down’ asymmetry away from zero by about 10 standard deviations, putting the phenomena of neutrino oscillations on firm experimental footing³[2].

Soudan-2 and MACRO experiments, both of which are based on iron calorimeters have further confirmed the hypothesis that atmospheric neutrinos do oscillate and hence removing any suspicions regarding this phenomena being observed only at water Cerenkov detectors, perhaps due to some systematic errors particular to those detectors. In the recent years, two experiments K2K and MINOS have further reduced the errors in the measurement of the oscillation parameters associated with the atmospheric neutrinos. They are now given to be as[4] :

$$\begin{aligned} \Delta m_{\text{atm}}^2 &= 2.6 \pm 0.2(0.6) \times 10^{-3} \text{eV}^2 \\ \theta_{\text{atm}} &= 43.3_{-3.8}^{+4.3}({}_{-8.8}^{+9.8}) \text{deg}, \end{aligned} \quad (6)$$

where as before we have quoted the 1σ (3σ) error bars.

Given these numbers for the mass squared differences and the mixing angles, we are now ready to reconstruct from the experimental data the neutrino mass matrix [5]. As mentioned in the introduction, the Standard Model of particle physics has made no provisions for non-zero neutrino masses. To accommodate for non-zero neutrino masses, several extensions of the Standard Model

³ The up-down asymmetry is expected to be zero if there are no oscillations.

have been considered. Experimentally, however a few issues still need to be settled. These are (i) whether neutrinos are of Majorana nature or Dirac nature. This determines whether neutrinos are anti-particles of themselves or not. This important issue could be tested in future neutrinoless double beta decay experiments whose transitions are only possible if neutrinos are Majorana (self anti-particles) in nature. This also has implications for the structure of the neutrino mass matrix as, in the Majorana case, the mass matrix is complex symmetric whereas in the Dirac case its complex generic. (ii) The second issue is related to the point that we have so far measured only the mass squared differences of the neutrinos but, not their absolute masses. With three neutrinos, we can have the observed mass squared differences in three different hierarchies (a) Normal Hierarchy (NH) $m_{\nu_1} \ll m_{\nu_2} \ll m_{\nu_3}$; (b) Inverted Hierarchy (IH) $m_{\nu_3} \ll m_{\nu_1} \ll m_{\nu_2}$; (c) Degenerate $m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3}$. Future experiments based on cosmology, long base line neutrino propagation and perhaps even neutrino less double beta decay are expected to shed light on this important aspect of the neutrino mass hierarchy. (iii) We have not yet measured the third neutrino mixing angle θ_{13} which appears in the three neutrino mixing scheme. At present there is only an upper bound from the CHOOZ experiment in France and its present limits are given as $\theta_{13} = 0^{+5.2}_{-0.0}({}^{+11.5}_{-0.0})$ deg. Future experiments like Double CHOOZ in France and Daya Bay in China are expected to improve this limit by at least an order of magnitude. (iv) Finally we have the question whether CP (a product of Charge conjugation symmetry and Parity)⁴ is a good symmetry or not in the leptonic sector. Experimentally this question is quite challenging and it crucially depends on the value of unknown neutrino mixing angle θ_{13} . Future experiments will hopefully be able to uncover this mystery.

One of the most popular and simplest extensions of the Standard Model gives neutrino masses through the so-called *see-saw* mechanism. In this mechanism right handed neutrinos are added to the standard model particle spectrum. Given that these particles do not obey Standard Model symmetries, they can have very large masses however breaking lepton number. At the same time, they can couple with the Standard Model (left handed) neutrinos resulting in a lepton number conserving (Dirac) mass, which can be expected to be close to one of the masses of the other Standard Model particles like top quark, bottom quark or tau lepton etc. The interplay between the large Majorana mass and the Dirac mass leads to a small non-vanishing mass \sim eV to the SM left handed neutrinos, just as what is expected by the experiments. It would be instructive to see

⁴ This symmetry plays an important role in our understanding of the origins of matter and anti-matter asymmetry in our world.

what the structure of the neutrino mass matrix is as demanded by the data. In the below, we will assume that neutrinos are Majorana in nature (as indicated by the seesaw mechanism) and further follow normal hierarchy (NH). In such a scheme, the neutrino mass matrix is given by :

$$\mathcal{M}_\nu = U_{\text{PMNS}}^* \mathcal{M}_{\text{diag}} U_{\text{PMNS}}^\dagger, \quad (7)$$

where $\mathcal{M}_{\text{diag}} = \text{Diag}\{m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\}$, with $m_{\nu_1} \ll \sqrt{\Delta m_{\text{solar}}^2}$, $m_{\nu_2} \sim \sqrt{\Delta m_{\text{solar}}^2}$, $m_{\nu_3} \sim \sqrt{\Delta m_{\text{atm}}^2}$. Neglecting the phases, the U_{PMNS} has the form (at 3σ level) given by [4] :

$$U_{\text{PMNS}} = \begin{pmatrix} 0.79 - 0.86 & 0.50 - 0.61 & 0.0 - 0.20 \\ 0.25 - 0.53 & 0.47 - 0.73 & 0.56 - 0.79 \\ 0.21 - 0.51 & 0.42 - 0.69 & 0.61 - 0.83 \end{pmatrix} \quad (8)$$

Considering the values for the individual neutrino masses depending on the scheme, one can reconstruct the neutrino mass matrix. This summarises the present status of three neutrino mixing and oscillations as we understand now.

III. LSND AND KARMEN : INDICATIONS FOR A STERILE NEUTRINO

While the search for a robust signal in solar and atmospheric neutrino oscillations was going on, simultaneously experimentalists have been on the look out for neutrino oscillations at other frequencies (ie, at Δm^2 other than those relevant for solar and atmospheric neutrino oscillations). Most of these earlier experiments had short base lines, typically about few tens of meters⁵ and are thus sensitive to $\Delta m^2 \gtrsim 1\text{eV}^2$. The LSND was one such experiment. Another important characteristic of the LSND experiment was that it was an appearance experiment. Typically, we can think of two types of strategies while looking for neutrino oscillations :

(a) Disappearance experiments: Here, we look for a reduction in the expected number of the neutrinos (which are detected) of a particular flavour. Then this disappearance is explained in terms of neutrino oscillations (in to undetected flavours).

(b) Appearance experiments: In other case, we can look for neutrino flavours which are either not present or very weakly produced at the neutrino source. Again this appearance is explained in terms of neutrino oscillations. It should be noted that earlier short based lined experiments have not found any evidence for neutrino oscillations. The initial indications for oscillations in both solar and atmospheric sectors have come from various disappearance experiments.

⁵ To probe solar and atmospheric neutrino oscillations on earth, one would need much larger base lines.

The LSND was based at Los Alamos National Laboratory (LANL) in United States. LSND, which stands for Liquid Scintillation Neutrino Detector had a base line of 30 Meters and was looking for an excess of ν_e , $\bar{\nu}_e$, starting from a beam which was mainly made up of ν_μ (and $\bar{\nu}_\mu$). The LSND has collected data from 1993 up to 1998, and the collaboration first reported ‘evidence’ for anti-neutrino oscillations in 1995, thus becoming the first experiment to report observation of neutrino oscillations using appearance type strategy.

The experimental set up is quite simple[6]. The source of neutrinos was an intense proton beam at the Los Alamos Meson Physics Facility (LAMPF) whose kinetic energy is 800 MeV (1 m A current). This beam was made to hit a water target, followed by a water-cooled Copper (Cu) beam dump. This produces large numbers of pions, mostly π^+ . The π^+ decays in to a μ^+ and ν_μ and $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$. Not many electron anti-neutrinos ($\bar{\nu}_e$) are expected from such a source (small amounts of π^- are produced, but are immediately absorbed, a few of them decay to μ^- , which are also absorbed before decaying). As mentioned earlier, the LSND detector itself was situated about 30 Meters from the source. The detector is approximately a cylindrical tank 8.3 Meters long and of 5.7 Meters diameter. It contained 167 tonnes of mineral oil (CH_2) and 0.031 g/litre of b-PBD (butyl-phenyl-bipheny-oxydiazole) which acted as the organic scintillating medium filling the detector. The detector is lined up with phototubes (1220 in number, 8-inch in size and of Hamamatsu make) inside the tank to detect the Cherenkov radiation as well as the scintillation light emitted from the propagating particle inside the detector. Further the detector was adequately shielded from cosmic rays by an overburden of roughly 2 Kg/cm².

Data was collected in two batches from 1993 to 1995 using the water target in the neutrino source described above and later replacing the water target with a closely packed high atomic number element (Z) from 1996 to 1998. Data from two types of decay patterns of μ ons was collected (i) μ decay at rest : used for the analysis of anti-neutrinos (ii) μ decay in flight : used for the analysis for neutrinos. A total of 18×10^{22} (*i.e.*, a trillion-billion, 180,000,000,000,000,000,000,000) protons were made to hit the LSND target during this period. The following reactions were used to detect the $\bar{\nu}_e$ emanating from μ decays at rest:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (9)$$

and the 2.2 MeV γ from the reaction

$$n + p \rightarrow d + \gamma. \quad (10)$$

In the case of μ decays in flight, the experiment looked for electron neutrinos which are expected to be present after oscillations of the muon neutrinos during the flight. The reaction used to detect

the electron neutrino was

$$\nu_e + {}^{12}\text{C} \rightarrow e^- + X \quad (11)$$

the signal being the single electron, where X stands for the residue of the ${}^{12}\text{C}$ atom due to this inelastic scattering.

In the data analysis, the energy range was taken to be $20 < E_e < 60$ MeV for the $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation search and $60 < E_e < 200$ MeV for the $\nu_\mu \rightarrow \nu_e$ oscillation search. In the anti-neutrino oscillation search, a total excess of $87.9 \pm 22.4 \pm 6.0$ events (3.8σ) consistent with $\overline{\nu}_e + p \rightarrow e^+ + n$ scattering was observed above the background. This excess corresponds to an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)$ percent assuming the the two anti-neutrino oscillation hypothesis. The neutrino oscillation search, in addition to the anti-neutrino search also found an excess of events though statistically, this excess was not significant. It amounted to $8.1 \pm 12.2 \pm 1.7$ events corresponding to an oscillation probability of $(0.10 \pm 0.16 \pm 0.04)\%$. To summarise, the LSND data suggested that (anti)neutrino oscillation occurred with a Δm^2 in the range of 0.2 to $10 \text{ eV}^2/c^4$. At 90 percent C.L. analysis of the μ^+ decay at rest data showed that $\sin^2 2\theta \in [10^{-3} \text{ to } 10^{-1}]$.

The implications of the LSND result are many fold : firstly, it indicates that the standard three flavour picture which we have summarised in the previous section would not longer hold true as with three neutrinos, one can have only two independent mass squared differences. This can be easily seen as follows ; the mass squared differences Δm_{ab}^2 as defined below eq.(1), satisfy the following equation in three generations : $\Delta m_{21}^2 + \Delta m_{32}^2 + \Delta m_{13}^2 = 0$, which shows there are only two independent mass squared differences in three generations. Secondly, if there is another neutrino responsible for the oscillations observed at LSND, this neutrino cannot be a part of the Standard Model families, as it would violate the experimental result from the LEP experiment at CERN, which said that there are only three families of neutrinos which take part in the Standard Model (more precisely weak) interactions. Thus the new neutrino has to be a *inert* under these interactions and thus named as a *sterile* neutrino.

Theoretically, the existence of a sterile neutrino would require deeper understanding of such particles[5]. Further newer mechanisms might be required to generate masses to them which can sometimes lead to complicated model building beyond the Standard Model. Phenomenologically too, simplest extensions from the three neutrino scheme to the four neutrino scheme, including a sterile neutrinos to accommodate the LSND data have run in to rough weather with improving measurements of solar and atmospheric data which have serious implications on such schemes. This is because little room is left to accommodate a sterile neutrino either in the solar data or in the

atmospheric data. Finally the sterile neutrino can only be tested indirectly. Indications can come from neutrino oscillations and perhaps through cosmology where sterile neutrinos can play a role in structure formation. Sterile neutrinos also have severe constraints from astrophysical processes like supernovae cooling etc[7]. While all these would pose new exciting challenges, the existence of a sterile neutrino experimentally relied only on the LSND data.

The sterile neutrinos are not the only solution offered to understand LSND data. Several new exotic ideas as well as some well motivated theories were used to explain the LSND data. For example, within supersymmetric extensions of the standard model new kinds of interactions which violate lepton number can be used to explain the LSND excess events. On the other hand, well motivated models based on theories of extra space dimensions also have a natural way of incorporating sterile neutrinos and LSND data[8]. In addition to these, more exotic ideas like CPT violation[9], which advocates different masses for particles and anti-particles and ideas of mass varying neutrinos which propose neutrino masses vary with time over cosmological time scales have been put to use explain to the LSND data in the recent years.

A. The KARMEN experiment

The LSND result ran in to controversy when some experimentalists have raised objections on the estimation of systematical errors of the experiment. The LSND collaboration has responded to these concerns by changing the target (from water to a closely packed high Z target) and further explaining that there could not be large errors introduced in to the systematics due to the presence of other sources of electron anti-neutrinos in the experiment. The KARMEN experiment, which was studying neutrino-nucleus cross sections around that time was expected to provide an independent confirmation or verification of the LSND observations after some modifications to their existing experimental set up.

This experiment whose acronym reads KARMEN (KArlsruhe Rutherford Medium Energy Neutrino) was located at the highly pulsed spallation neutron source ISIS of the Rutherford Laboratory (UK). The experiment was most sensitive to the search of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation channel.

In this case, a rapid cycle synchrotron is used to accelerate the protons upto 800 MeV with a design beam current of 200 μ A. The protons are made to hit a target of water-cooled Ta-D₂O, which produced π^+ , which decays then in to μ^+ ; the subsequent decays of μ^+ act as a source of anti-muon neutrinos. The detector which is a segmented high resolution liquid scintillation calorimeter, is located at a mean distance of 17.7 Meters from the target. The liquid scintillator

consists of a mixture of paraffin oil (75 percent by volume), pseudocumene (25 percent by volume) and 2 g l^{-1} of the scintillating active 1-phenyl-3-mesityl-2-pyrazoline(PMP). Appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ flavour oscillation. is detected by the classical inverse beta-decay reaction:

$$\begin{aligned}\bar{\nu}_e + p &\rightarrow n + e^+ \quad Q = -1.804 \text{ MeV} \\ n_{th} + {}^1H &\rightarrow {}^2H + \gamma \\ n_{th} + Gd &\rightarrow Gd + n\gamma,\end{aligned}\tag{12}$$

where, the average number of photons emitted , $\langle n \rangle = 3$. In total 15 candidates fulfilled all conditions for the $\bar{\nu}_e$ signature. This agreed with the background expectation of 15.8 ± 0.5 events. Hence there was no signature of oscillations. Analysis of the data yielded the following results: $\sin^2 2\theta < 1.7 \times 10^{-3}$ for $\Delta m^2 \geq 100 \text{ eV}^2$ and $\Delta m^2 < 0.055 \text{ eV}^2$ for $\sin^2 2\theta = 1$ at 90 % CL. The implications are that at large Δm^2 , KARMEN results exclude the region favoured by LSND. At low Δm^2 there is a restricted parameter region statistically compatible with both the experimental results. A joint analysis with LSND shows that these results are 64 percent compatible with each other[10].

IV. MINIBOONE

In order to address the LSND anomaly the MiniBooNE (BooNE is an acronym for the Booster Neutrino Experiment) experiment was proposed. The MiniBooNE collaborators have kept the L/E same as in LSND but have changed the systematics, energy and the event signature. This way, one has access to the entire parameter space accessed by LSND.

MiniBooNE is located at the Fermi National Accelerator Laboratory, Batavia, IL, in the United States. The experiment made use of the Fermilab Booster neutrino beam. Protons with energies of 8 GeV were incident on a Beryllium (Be) target; such a choice of the target solely being dictated by the need of a source with far more μ^+ 's than μ^- 's. To increase the flux, a magnetic focusing horn which encloses the target has been used (this increases the flux almost six fold). A total 6.3×10^{12} POT were delivered, while the actual result of the experiment corresponded to $(5.58 \pm 0.12) \times 10^{12}$ POT[11].

This experiment was also based on the ‘appearance’ principle ; it had looked for an excess of ν_e in a purely ν_μ beam. After the protons hit the target, the produced (positively charged) pions and kaons pass through a collimator of about 60 cm long and then through a tunnel towards the detector which is about 50 m long. These particles decay along the way producing neutrinos. The

‘intrinsic’ $\nu_e + \overline{\nu}_e$ sources are: $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$ (52 percent) $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ (29 percent) $K^0 \rightarrow \pi + e + \nu_e$ (14 percent) others (5 percent) ; $\nu_e/\nu_\mu = 0.5$ percent and the anti-neutrino content is about 6 percent.

The detector is placed about 541 m downstream in front of the target. It has the shape of a sphere, 12.2 m in diameter. This spherical tank is filled up with 800 tonnes of pure mineral oil (fiducial volume = 450 tonnes ⁶). An optical barrier separates the detector into 2 regions (a) an inner light-tight volume of radius 575 cm and (b) an optically isolated outer volume 35 cm thick known as veto region. The optical barrier is lined with 1280 inner photomultiplier tubes (PMT) (8-inch) providing 10 percent photocathode coverage. An additional 240 veto phototubes are lined in the inner volume detecting particles entering or leaving the detector.

The produced neutrinos traverse along the tunnel, enter the detector, and interact with the medium in the detector. Depending on the pattern of light observed in the PMTs, one can determine the kind of interaction the neutrino went through in the detector. Two signatures (a) Cherenkov radiation and (b) scintillation (fluorescence) light are used to detect the kind of neutrino interaction. Neutrinos interact through both charged current and neutral current channels here and both are used in the detection process. The main interactions are (1) Charged-current scattering (39 percent), (2) Neutral current(NC) elastic scattering (16 percent), (3) Charged-current (CC) single pion production (29 percent) (4) NC single pion production (12 percent), (5) Multi-pion and deep-inelastic scattering (less than 5 percent). The list of all possible interactions and the corresponding signature in the PMT can be found in the research paper put out by the collaboration[11]. For example, in the charged- current quasi-elastic events, a neutrino interaction in the detector will produce the lepton partner of the neutrino. Electrons multiple-scatter along their way and so travel for a very short time before their velocity falls below that required for Cherenkov radiation. Hence a fuzzy Cherenkov ring in the detector is their signature. Muons, being heavier, have much longer tracks. As they slow down, the angle at which the Cherenkov light is being emitted shrinks. Muons also emit scintillation light. The signature is a sharp outer ring with fuzzy inner region. Neutral pions decay into 2 photons which then pair-produce (an electron and a positron). Evidently their signature in the detector are two fuzzy rings.

Data was collected for about five years starting from 2002. After the data was taken, the MiniBooNE collaboration performed a ”blind” analysis. This means the experimentalists did not have access to all the information in the data. This is one of the hallmarks of the work done

⁶ Actual volume relevant in the detection process.

by this collaboration. For oscillation search two different types of analysis were performed : one which depended on likelihood variables (called the "Track Based" ,TB analysis), and the one which depended on a boosted decision tree. In this way, each analysis would cross-check the other analysis. In the published analysis, the former algorithm was chosen as the primary result because it had a better sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation. In the analysis, the electron neutrino events were isolated and then a comparison is made between the observed number of events to the expected number of events (that is the sum of the intrinsic electron neutrino and the fake events) as a function of the 'reconstructed' neutrino energy. An excess of the observed data over expected data (or an excess of ν_e events) as a function of the energy indicates oscillation.

After the complete analysis was done "the box" was opened : it was found that there was no significant excess of events ($22 \pm 19 \pm 35$ events) for $475 < E_\nu^{QE} < 1250$ MeV. The oscillation fit in the $475 < E_\nu^{QE} < 1250$ MeV range yields a χ^2 probability of 93 percent for the null hypothesis, and a probability of 99 percent for the ($\sin^2\theta = 10^{-3}$, $\Delta m^2 = 4 \text{ eV}^2$) for the best-fit point. The probability that MiniBooNE and LSND both are due to two-neutrino oscillations is only 2 percent⁷.

V. IMPLICATIONS OF MINIBOONE AND FUTURE DIRECTIONS

The MiniBooNE's results will have strong implications for most of the sterile neutrino models which are constructed as extensions of the Standard Model. However, before that the MiniBooNE still has some things which have to be understood about its own analysis. The experiment has reported an excess of events ($96 \pm 17 \pm 20$ events) (deviation = 3.7σ) was observed below 475 MeV above the expected background. Presently, very little understanding is present about the source of this excess. It is not clear whether it is an experimental systematical error or whether it signals the existence of new physics.

One of the major implications of the MiniBooNE result is that simplest sterile neutrino schemes, like $3 + 1$ or $2 + 2$ with single sterile neutrino are ruled out as they are not compatible with both LSND and MiniBooNE data. However, the exploiting CP violation present in much larger schemes like $3 + 2$ with two sterile neutrinos can still accommodate LSND and MiniBooNE data making them compatible[13]. The case of this larger $3 + 2$ framework has implications also for astrophysical neutrinos, especially neutrinos involved in supernovae[14]. It is also proposed that sterile neutrino

⁷ This result is only true as long as one restricts Δm^2 from 0.2 to 2.75 eV²[12]. A recent analysis by MiniBooNE collaboration finds that there is a non-negligible probability that the results from all the three experiments, namely, LSND, Karmen and Mini BooNE are due to a two-neutrino oscillation if the Δm^2 is taken to be much lower[12].

signatures can be found at neutrino telescopes probing ultra high energy neutrinos[15].

Mass varying neutrinos have been proposed as means of generating the cosmological dark energy in the recent years. Here the neutrinos have couplings to an *acceleron* field which vary over cosmological times scales. This idea has been applied to explain the LSND data. Just as in the three neutrino case, here too one would need to add another neutrino to accommodate the LSND data as we would need at least one more mass squared difference in addition to the ones required. It has been pointed out that in this particular model[16], it could happen that there could be positive signal at LSND whereas a null result for MiniBoone. How far this idea would remain viable with future long based experiments remains to be seen.

While CPT violation need is not completely understood within the context of quantum field theory, in the neutrino sector it can be incorporated by assuming neutrinos and anti-neutrinos have different masses and mixing angles and thus the oscillation frequencies of neutrinos and anti-neutrinos would be different. This has been utilised to explain the LSND data. However after the KamLand experiment, there has been some skepticism though it was shown that statistically the fits could be still reasonable. The fate of a four[17] or high number of neutrino generation CPT violating models needs to be seen.

Thus, at present the last word has not yet been said about the fascinating world of sterile neutrinos. As MiniBooNE continues to take data, we expect more severe constraints from them.

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- [1] B. Pontecorvo, “Mesonium and antimesonium,” Sov. Phys. JETP **6**, 429 (1957) [Zh. Eksp. Teor. Fiz. **33**, 549 (1957)] ;
S. M. Bilenky and B. Pontecorvo, “Lepton Mixing And Neutrino Oscillations,” Phys. Rept. **41**, 225 (1978).
 - [2] S. M. Bilenky, C. Giunti and W. Grimus, “Phenomenology of neutrino oscillations,” Prog. Part. Nucl. Phys. **43**, 1 (1999) [arXiv:hep-ph/9812360].
 - [3] See for example, articles of B. Ananthanarayan and R. K. Singh, “Direct observation of neutrino oscillations at the Sudbury Neutrino Observatory,” Curr. Sci. **83**, 553 (2002) [Resonance J. Sci. Educ. **7N10**, 79 (2002 ERRAT,8N1,88.2003)] [arXiv:physics/0208096] ;
B. Ananthanarayan, C. Gautham, A. Mavalankar, K. Shivaraj, S. Uma Sankar and A. Upadhyay, “Research news: Progress in determination of neutrino oscillation parameters,” Curr. Sci. **91**, 864

- (2006) [arXiv:physics/0608152] and references there in.
- [4] For a recent reviews see, S. Goswami, A. Bandyopadhyay and S. Choubey, “Global analysis of neutrino oscillation,” Nucl. Phys. Proc. Suppl. **143**, 121 (2005) [arXiv:hep-ph/0409224] ;
M. C. Gonzalez-Garcia and M. Maltoni, “Phenomenology with Massive Neutrinos,” arXiv:0704.1800 [hep-ph].
 - [5] See for example, the following resource papers : R. N. Mohapatra *et al.*, “Theory of neutrinos,” arXiv:hep-ph/0412099 ;
R. N. Mohapatra *et al.*, “Theory of neutrinos: A white paper,” arXiv:hep-ph/0510213.
 - [6] C. Athanassopoulos *et al.* [LSND Collaboration], “Evidence for anti- $\nu/\mu \rightarrow \bar{\nu}$ anti- ν/e oscillation from the LSND experiment at the Los Alamos Meson Physics Facility,” Phys. Rev. Lett. **77**, 3082 (1996) [arXiv:nucl-ex/9605003] ;
A. Aguilar *et al.* [LSND Collaboration], “Evidence for neutrino oscillations from the observation of anti- ν/e appearance in a anti- ν/μ beam,” Phys. Rev. D **64**, 112007 (2001) [arXiv:hep-ex/0104049].
 - [7] For a nice review on sterile neutrinos, please see M. Cirelli, G. Marandella, A. Strumia and F. Vissani, “Probing oscillations into sterile neutrinos with cosmology, astrophysics and experiments,” Nucl. Phys. B **708**, 215 (2005) [arXiv:hep-ph/0403158].
 - [8] K. R. Dienes, E. Dudas and T. Gherghetta, “Light neutrinos without heavy mass scales: A higher-dimensional seesaw mechanism,” Nucl. Phys. B **557**, 25 (1999) [arXiv:hep-ph/9811428].
 - [9] G. Barenboim, L. Borissov, J. D. Lykken and A. Y. Smirnov, “Neutrinos as the messengers of CPT violation,” JHEP **0210**, 001 (2002) [arXiv:hep-ph/0108199] ;
H. Murayama and T. Yanagida, “LSND, SN1987A, and CPT violation,” Phys. Lett. B **520**, 263 (2001) [arXiv:hep-ph/0010178].
 - [10] B. Armbruster *et al.* [KARMEN Collaboration], “Upper limits for neutrino oscillations anti- $\nu/\mu \rightarrow \bar{\nu}$ anti- ν/e from muon decay at rest,” Phys. Rev. D **65**, 112001 (2002) [arXiv:hep-ex/0203021].
 - [11] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], “A Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1 \text{ eV}^2$ Scale,” Phys. Rev. Lett. **98**, 231801 (2007) [arXiv:0704.1500 [hep-ex]]; See also, the website : <http://www-boone.fnal.gov/> and links there in.
 - [12] Heather Ray, Mini BooNE collaboration, by private communication.
 - [13] M. Maltoni and T. Schwetz, “Sterile neutrino oscillations after first MiniBooNE results,” arXiv:0705.0107 [hep-ph];
S. Goswami and W. Rodejohann, “MiniBooNE Results and Neutrino Schemes with 2 sterile Neutrinos: Possible Mass Orderings and Observables related to Neutrino Masses,” arXiv:0706.1462 [hep-ph].
 - [14] S. Choubey, N. P. Harries and G. G. Ross, Phys. Rev. D **74**, 053010 (2006) [arXiv:hep-ph/0605255];
S. Choubey, N. P. Harries and G. G. Ross, Phys. Rev. D **76**, 073013 (2007) [arXiv:hep-ph/0703092].
 - [15] R. L. Awasthi and S. Choubey, arXiv:0706.0399 [hep-ph]; S. Choubey, arXiv:0709.1937 [hep-ph].
 - [16] V. Barger, D. Marfatia and K. Whisnant, “Confronting mass-varying neutrinos with MiniBooNE,” Phys. Rev. D **73**, 013005 (2006) [arXiv:hep-ph/0509163].

- [17] V. Barger, D. Marfatia and K. Whisnant, “LSND anomaly from CPT violation in four-neutrino models,” *Phys. Lett. B* **576**, 303 (2003) [arXiv:hep-ph/0308299].